

Development of a Robotic Torque Application Gripper for Automated Furniture Assembly

by

John Romanishin

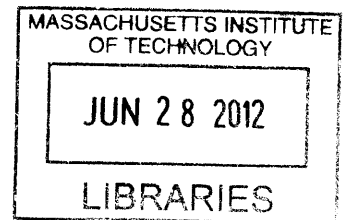
Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Engineering as Recommended by the
Department of Mechanical Engineering

at the

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June 2012

ARCHIVES



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ABSTRACT

This thesis describes the redesign of a robotic claw end-effector originally built for the MIT class 6.142. The claw was designed in order to assist an autonomous furniture assembly robotic project by spinning. The project used KUKA youbots in order to assemble IKEA Lak tables. The first generation of the claw was designed and built very quickly out of laser-cut materials and is described briefly. This final version was designed to be a high-quality machine, with an emphasis placed on the weight and form, and performance.

After a brief introduction, my design philosophy that guided the process is briefly described. Next the specific details of the design are described. The design and FEA analysis of the frame in order to optimize weight and strength are discussed, as well as the design of the fluid damping device. The power train design and analysis is then briefly described with an emphasis on efficiency and evaluating the usefulness of the approach that I took. The next area of concern is a characterization of the kinematics of the grasping elastic encirclement members that grasp the object, followed by a discussion of the lessons learned.

Thesis Supervisor: Daniela Rus

Title: Professor of Computer Science and Electrical Engineering

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1. Project Introduction and Context

1.1 Autonomous Robotic Construction and Assembly

While robots now dominate manufacturing processes in much of the world, most things that are built or assembled outside of the factory still use humans. For example the assembly of buildings, furniture, reconfiguration of spaces (such as for concerts), is still almost all entirely accomplished by humans. There are many reasons why this area has been so difficult for robots to take over. One significant problem with many existing robots is that they are currently considered to be too dangerous to interact with people. Most existing robotic appendages have great power and accuracy, but lack the flexibility, softness and responsiveness necessary to interact with untrained humans. This has greatly limited the crossover of industrial robot technology into applications outside the factory. Since there is less money to develop the same sort of capabilities that exist in industrial robots to in-house robots, there has not been the same level of commercial focus on developing compliant robots that work in the same way as humans [1]. The second reason is that the world outside of the factory is less conducive technically for robots. The large challenges which are largely mitigated in the factory environment including localization, sensing and dealing with unexpected problems and events, are still largely the domain of humans [1]. However increasing interest in this field seems to be developing as demonstrated through robots such as IRobot's robotic vacuum [1] or the promised new revolution of Rodney Brookes' company Heartland Robotics [2]. As robot technology continues to develop at breakneck speed, there is likely to be a renaissance of robots that perform tasks outside of the factory working directly with humans including possibly the assembly of your next furniture set from Ikea.

1.2 Challenge: Furniture Assembly

This work addresses the robotic assembly in the context of a grand challenge problem, furniture assembly. We tackle this broad challenge using a simple task, how can mobile manipulators such as the Kuka youbot robots cooperate to assemble an Ikea Lak coffee table (right 1-1). A critical operation in assembling IKEA furniture is screwing components together – for example to connect the legs to the coffee table top. Our challenge is to develop a fixture that will enable the youbot robots to screw in components of different sizes, such as the table legs. In this project we focus on the manipulation aspect of this task. We abstract away the control and localization problems as well as robot coordination.



Figure 1-1 The components of the class challenge. On the left is the table, with four legs that had an approximately two inch square cross section. This was the item that needed to be attached by the robot. The robot is a miniature educational version of the German industrial robotics company Kuka's mobile robotic arm. [3]

The very significant problem of localization was abstracted away by using a system called opti-track, but this was only partially successful in providing the necessary resolution. The mechanical challenge became the design of a removable end-effector for the robotic arm that

could spin the table legs in order to attach them. This problem is difficult because the robot and the table were both fixed in position, so either exact precision, or some compliance in the mechanism was required. The main goal was to be able to make a device that could apply a torque to the table leg with a high level of compliance, but I wanted to go further – to design something that could work with many different objects besides the table leg. In the rest of this paper I will describe the device that resulted from this class project.

1.3 Solution Overview

The key insight was to develop a device that can grasp and spin objects by surrounding them with high friction elastic elements that constrict around the object. This can be accomplished by using two rings, with the elastic elements attached to each ring. The top ring is driven by motors, while the bottom ring has mechanical drag causing it to lag behind the other ring, as can be seen in Figure 1-2.

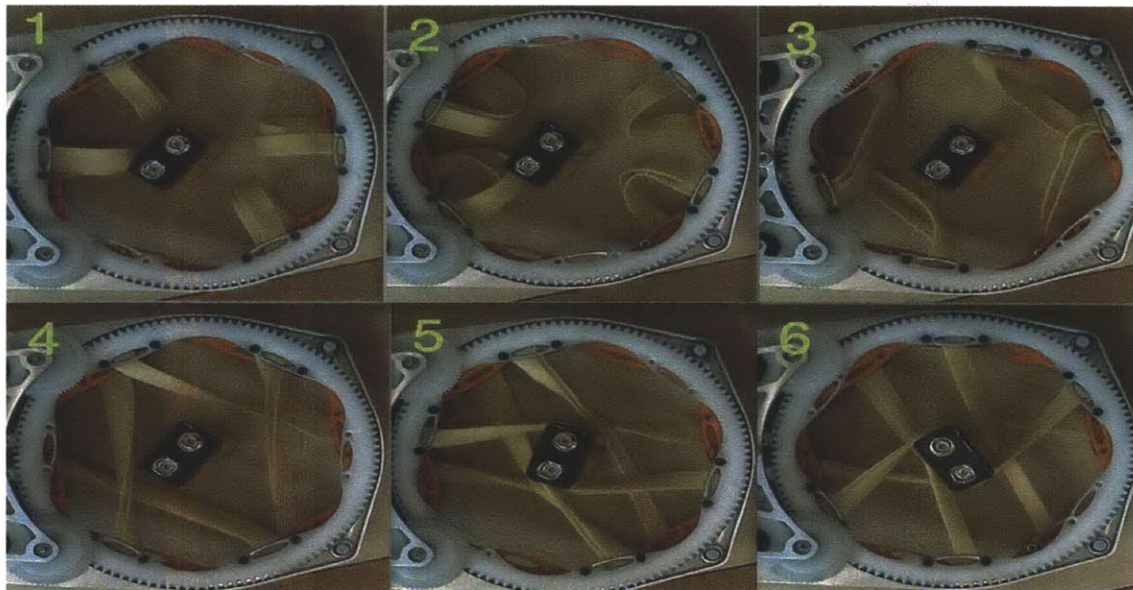


Figure 1-2 Claw operation demonstration. This shows a progression of the elastic elements as the newest version of the claw grips an object (a 9 volt battery). The claw can grasp almost any object that has been attempted, including among others, plastic bottles, cell phone, screw-drivers, camera lens, and coffee cups.

1.4 First Design Iteration

The initial design was chosen to be simple and robust to different object sizes. Next a first prototype was built. This prototype was put together over the span of three weeks using rapid prototype machining, primarily laser-cut sheets of plastic. There were many significant problems with this first design, however the prototype validated the feasibility of our proposed solution concept. The problems included a frictional damper that locked in place and jumped from one position to the next, as well as a very weak power train, and a you-bot attachment mechanism that did not work.

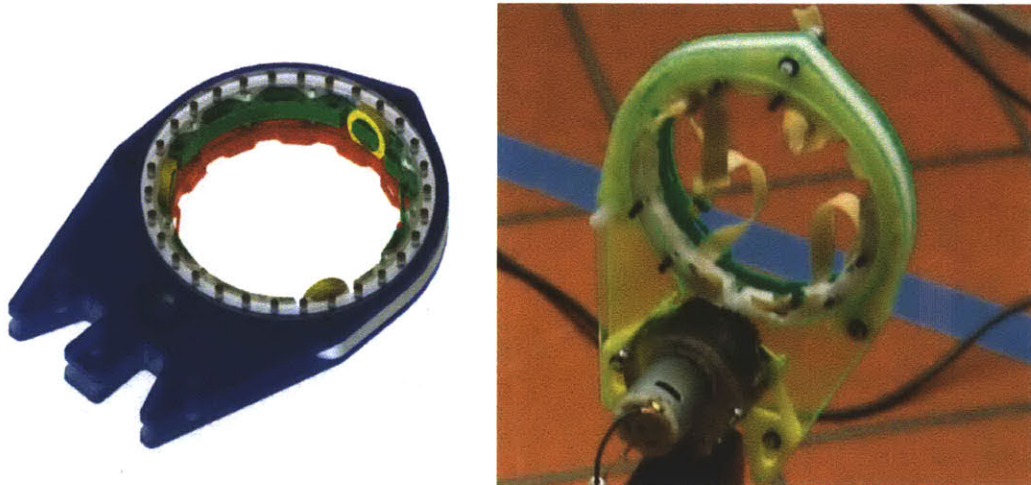


Figure 1-3 Overview of the initial prototype version of the claw built and designed for the class 6.142 in the fall semester of 2011. In both the Solidworks rendering (a) and the actual claw version (b).

The second prototype corrected the problems with the initial design, but it proved to be quite slow, heavy, and bulky. This design was able to successfully attach the table legs, although due to other issues, the process was never accomplished completely autonomously. The claw was powered by a prebuilt VS-11 servo that was mounted above the main ring element. Similar to the first design, it was constructed of mostly laser-cut materials. While the use of

multiple sheets of two dimensional laser-cut materials is a very quick way to prototype, it will almost never be as strong as a structure machined out of a single piece of material.

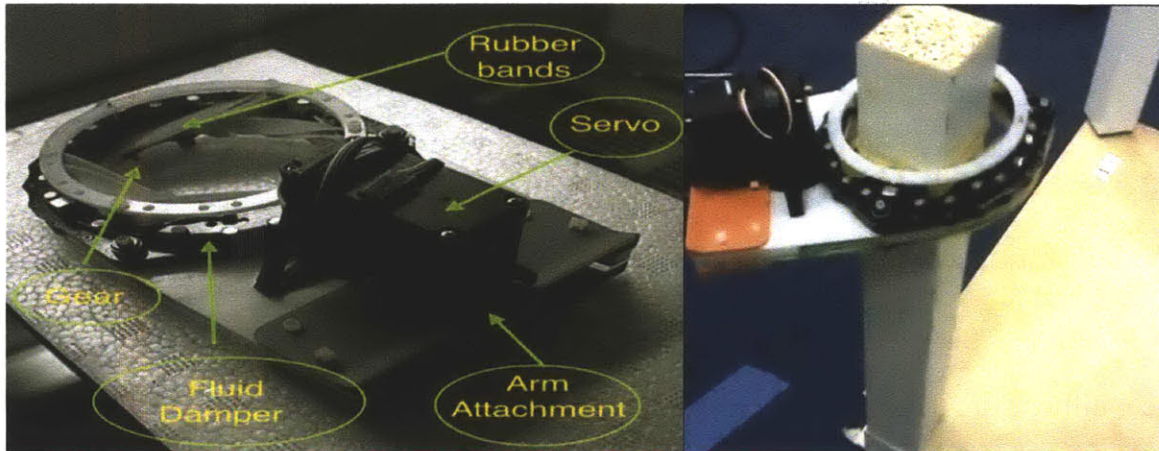


Figure 1-4 Overview of second claw built and designed for the class 6.142 in the fall of 2012. On the right is a snapshot from a you-tube video of the claw fixed to a Youbot attaching a leg to the Lak table. [4]

2. Design Process

2.1 General Design Process

Mechanical design is what I have been doing since I was two years old and building with Lego blocks. Design is my favorite aspect of mechanical engineering, and the very things that make it difficult are the things that draw me to it. There is often no set formula for designing, so creativity is often required in order to devise elegant solutions. The space of possible designs is almost infinitely large and there is a need to quickly and accurately consider an overwhelming amount of possibilities in order to be assured that the best design is chosen. The ability to effectively make these decisions comes primarily through intuition which comes from practice. However much intuition might be involved, it is also important to have and consider principles. The following are some of the principles that are important to me in the design process, and that I attempted to consciously apply to this thesis project. While these are in no means original principles, the important aspect is in the diligence and creativity with which they are applied to the challenges at hand.

2.2 Simplicity

In the words of Antoine de Saint-Exupery “perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away.”[5] This is perhaps the most important consideration that I aspire to apply to design, as well as life. While it is verging on axiomatic to say that we shouldn’t include that which is unnecessary, the value of implementing

this statement goes deeper. Consciously applying this principle to mechanical design involves many of the most fundamental problems of design. For example the decision of when to combine two parts into one, or whether to use a single process for multiple types of parts involves many different facets of the concept of simplicity. Ultimately the true interpretation of a concept such as simplicity becomes something almost undefinable, but somehow still at the core of my way of viewing the world of design.

2.3 Modularity

Modularity is a fundamental concept that underpins any set of interacting elements – whose importance cannot be over stressed. In application to almost all engineering systems, without a deliberate and thorough consideration of the way in which different components relate to each other complexity often leads to disorder. Modularity also allows systems or design to be reconfigurable and adaptable. Modularity is more than just ensuring that things have defined interfaces and definitions, it exists on many different levels in different systems. For example life is an excellent demonstrator of modularity – for example almost all living things share the same mechanism for replicating DNA, or making proteins.

2.4 Symmetry

Symmetry is a principle that underpins many of the other factors on this list. One of the primary reasons why symmetry is important is that it promotes simplicity, and modularity. Not only is the ability to design only half of one thing, or to use half the number of unique parts, a result of symmetry, but often its application solves many different complex problems that could arise. For example making an item symmetric about its axis of rotation not only makes it easier

to produce, but also prevents uneven wear on the drive system controlling it. As with the other principles there are many different ways and levels in which to implement symmetry while designing systems. Part of the reason why I hold symmetry to be so important is that I (like most people) [6] like the way that symmetric things look, but it also has a surprising ability to solve problems before they exist.

2.5 Designs for Manufacturing

This is more of a practical principle, but I think that it is essential in order to actually create things and move projects forward, and one that is often overlooked. Since most types of manufacturing processes are very expensive (although additive manufacturing systems are beginning to change this) [7] designing things that can actually be made not only makes them cheaper to make, but the lack of this actively prevents them to be made in the first place. Often times in order for money to be provided to a project there needs to be some type of demonstration or validation of a physical item – it is difficult to prove that a design on a computer screen will actually work. In this sense if an object is not only designed to be manufacturable using current technology – but also designed to be manufactured using the actual resources available to the designer (I don't have access to 3d metal laser machine) it will not be built.

2.6 Elegance

This principle is undeniably a little more subjective than the others, I think that often times its definition is the same as simplicity – but not exactly the same. Under this principle I also include various aesthetic considerations such as the continuation of line throughout objects

or the tendency to use single elements that achieve multiple functions out of a single process or part. Ultimately I think that elegance in design is simply the combination of applying good principles to a passionate design process

2.7 Application of these principles.

While nobody is perfect, the more one consciously considers and thinks objectively about the way they do things, the closer one can get to it. In that sense these principles are more goals than rules, principles that I have validated through experience and that I aspire towards, but do not always follow. I believe that one benefits from explicitly considering and talking about concepts that might appear simple and obvious at first glance. For it is a different thing to just know something, than to be obsessed by it, to not just understand it but to live it.

3. Mechanical Design of the Third Device

3.1 Design Overview

The device can be seen below in figure 3-1. The focus on this design iteration was to make the device much more robust, in both form and performance. The device is very similar to the previous version in terms of total dimensions and the intended use, but was designed with more detail, and built with improved materials and methods. The components that were focused on for the redesign in this project were the frame, the gear-train, the bearings and the attachment mechanism.

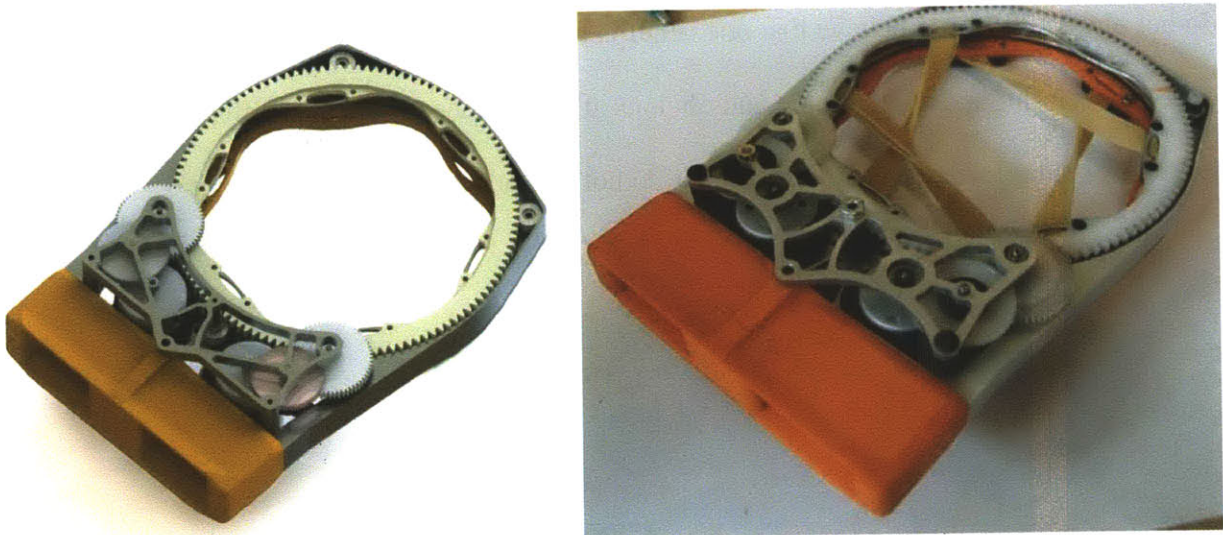


Figure 3-1 Image and rendering of the final device. Showing the 3d rendering of the final design alongside a picture of the final device. The key elements are apparent in the picture, including the drivetrain, the Aluminum frame, and the Kuka attach point (large orange box). On the bottom of the device not shown, are the drive motors, and the bottom ring.

3.2 Designing the Frame

The frame of a house is literally that which everything else is built upon. In this case, the frame of the claw is perhaps the most important component as it holds all of the other

components together. The frame from the first prototype was constructed out of three different layers of laser cut plastic as can be seen in figure 3-2. While layered structures can be very



Figure 3-2 Frame of prototype number two. Showing the layered approach taken with the second prototype. This frame was very heavy, over 120 grams, which is more than four times the weight of the new aluminum frame.

effective, as in the case of composites such as carbon fiber, it is often not the best way to achieve space savings, weight reduction, or precision. The new frame was designed to be CNC milled out of a single block of high performance 7075-T6 aluminum, thereby allowing for more features and taking advantage of the higher specific stiffness of aluminum as compared to plastic.

There is no existing conclusive deterministic method of designing elements that can perform their desired function while optimizing for weight. The best that the designer can do is to use intuition, application of known mechanical principles, and make many iterations. The existence of finite element analysis programs, such as COSMOS in Solidworks, greatly improves this ability. The design process involved first sketching the basic outline of the part – produced by taking the important interacting elements, drawing a shape around them, and then trying to

remove material where possible. The effects of the removal of material are then analysis by the FEA analysis to decide their utility.

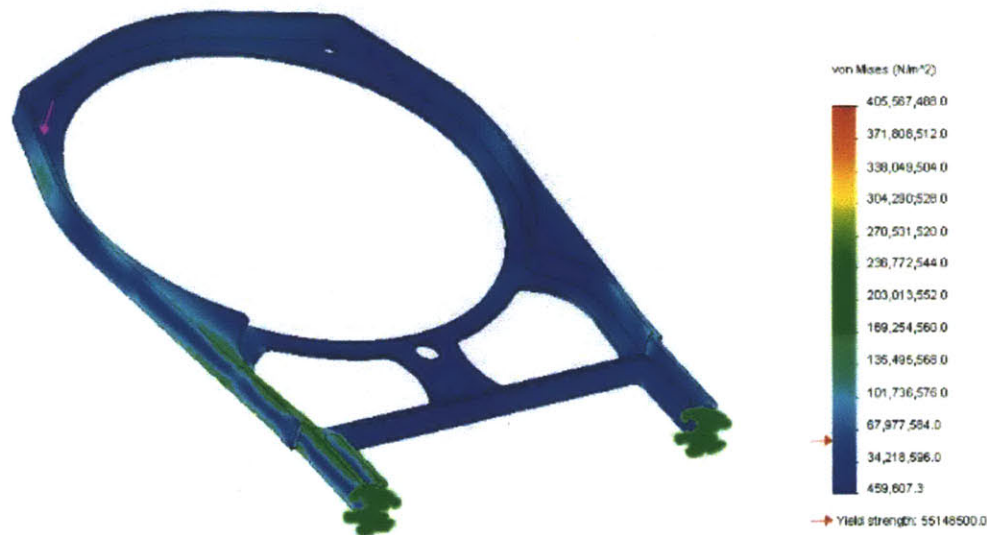


Figure 3-3. FEA of the claw's Frame. Showing performance of the frame when subject to simple beam bending. The bright areas are areas of high stress, and are therefore where the focus of the designer should be in order to ensure that the part doesn't break. In this case the area at the top and the bottom of the left side is shown to have very high stress, in the design process, this led to the creation of the much wider element that can be seen below in figure 4.

This case shows the how the intuitive principles such as symmetry can be used to improve the design ability. For an object like this which might experience various forces in an unknown environment, it is safe to assume that it could encounter equal forces from nearly every different direction. Using symmetry can help to make sure that this is realized, but symmetry about the right/left axis is easy, while about the top/bottom axis is a little bit more difficult. Since it is very difficult to machine undercuts which can produce the strong I-beam shape, through the insight of FEA this same effect was produced by making an the beam in the shape as shown in figure 3-4.



Figure 3-4. Cross section of Frame. Showing the design used in order to approximate an I beam in designing the claw's frame

This provides essentially the same performance in bending as an I-beam, but it can be milled easily using traditional milling equipment. The frame was milled on both the front and back out of a single block. The final rendering of the frame and a picture of it clamped in the mill as it is being constructed can be seen in figure 3-5.

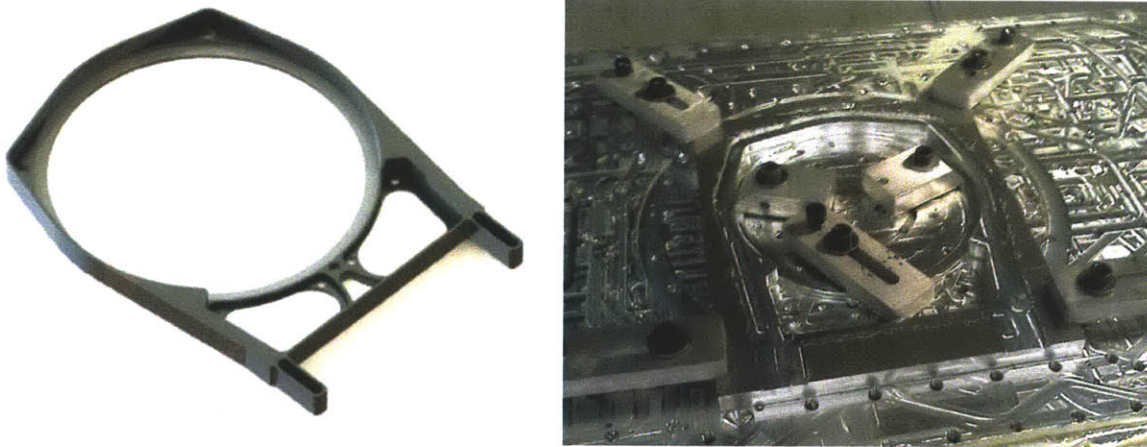


Figure 3-5. Claw Frame Detail. Rendering of the Aluminum frame, next to a photograph of the frame under production. This shows the amazing ability of CNC to produce exact copies of out metal.

3.3 Designing the Bearings

From observation as a student in and then as a lab assistant of 2.007 and general experience, the use of bearings in mechanical design is complex and often causes people many

problems. There countless reasons where one can go wrong in designing systems that use bearings including improper alignment, excessive forces due to cantilevered support or high friction caused by improper bearing type. Ball bearings compared to the best frictional bearings are at least an order of magnitude more efficient due to lack of any energy loss as a result of mechanical friction.[8] Bering design is important because they are precision elements that interface between different components and often handle high forces and speeds. At the same time however sometimes the selection of ball bearings as compared to sliding element bearings is sometimes unnecessary in terms of cost, stiffness, or complexity.

This was an issue I faced while re-designing the new claw. The old claw used ball bearings to constrain the spinning rings radially and simple sliding elements in order to constrain it radially. The new design involved the creation of a large custom thrust bearing that was designed to cause a minimum of friction, as can be seen in figure 3-6. The rotating ring in the new design is completely constrained by sliding element bearings, therefore increasing the efficiency and load capacity of the entire device.

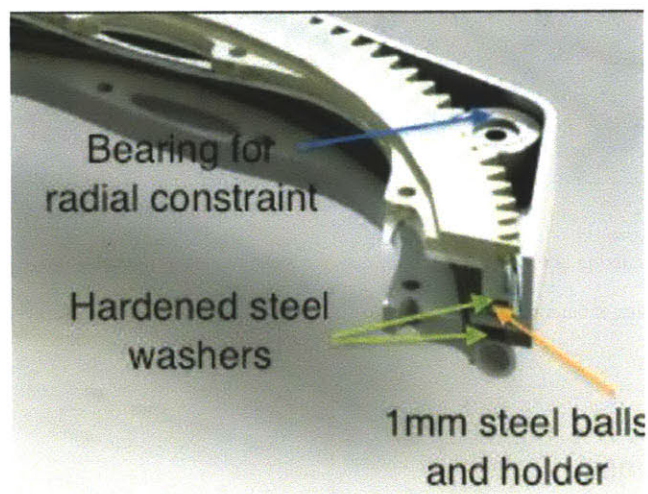


Figure 3-6. Claw bearings detail. Note the two thrust washers made of wear-resistant thin steel stock, the ball container, and the ball bearings combine to smoothly absorb thrust forces concentric to the ring of the device.

3.4 Designing the Frictional Damper

In the claw design there are two rotating rings attached to rubber bands, one of them must have a resistance in order to begin the stretching of the rubber bands, or they will just both spin without engaging the actual part. The functional requirements for such a device are essentially to act as a pure velocity dependent damper. Device based on static friction are not effective at meeting these requirements because stiction force causes friction to be highest when there is no movement, and then decreases to a constant as velocity increases. In order to make an actual damper, some type of fluid that could dissipate the energy was required. Last semester I designed a fluid damper ring that involved the dragging of metal balls through an thick oil by magnets placed on the frame as shown in figure 6. This worked in theory, but in practice the sealing was very difficult. I delicately turned two open faced Acetyl Polymer ring shaped pieces on the lathe in order to create the channel that the oil was going to fit in. However I failed to properly consider the difficulty that sealing this device would entail and oil constantly leaked from the device.

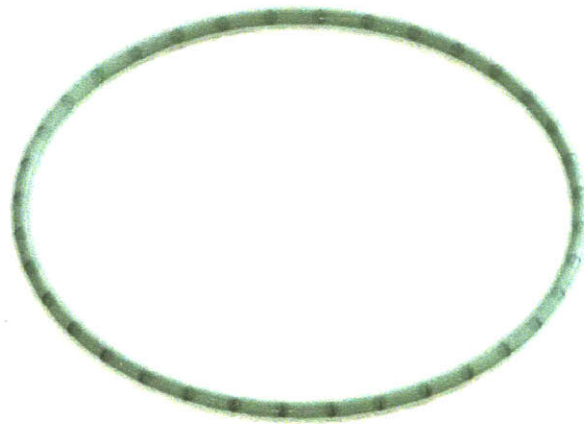


Figure 3-7. Damper Detail. Showing the inside of the old damper design as well as a solid rendering of the new simpler design which uses a prebuilt plastic tube.

This old design was not only difficult to manufacture, as it had over a 50cm of length that required sealing, it constantly leaked oil. The new design was figured out based on applying the design principle of simplicity. It was made by simply buying a plastic pipe and bending it into a donut shape, and then sealing the two ends together with tape. All together this required less than 2% of the sealing area as the previous design and was much easier to manufacture, this change demonstrated the principles of elegance and design for manufacture described earlier. However even this design had problems due to the oil interfering with the tape seal. In the version of the claw that was actually finished, this damper has been replaced by a simple sliding frictional design using a steel ring pulled towards the claw with magnets.

3.5 Modular Design

Since this is still a prototype, I was reluctant to combine too many different features into one single piece. By separating the features onto separate peaces, it allows for disassembly and improvement of specific pieces in the future. In order to do this I consciously made the interfaces between various components easy to change and improve in future versions of the claw. Since the aluminum frame element was the most complex and important part to make, I consciously avoided adding specific features such a hole to hold the motor to it. Pieces such as the gear-train bearing plates, and the robotic arm attachment point are provided by intermediate rapid prototype- producible pieces, and not the frame itself – so that if these should change only a new piece needs to remade, instead of machining the whole frame again. The design of these pieces can be seen in figure 3-8.



Figure 3-8. Modular assembly rendering. Showing the frame with the replaceable plastic items with specific features (Shown in green), including the claw attachment piece, and the motor and gear train mounts.

This type of design allows for modularity and adaptation of the design to new circumstances. For example if the Kuka robot gains a new type of claw mounting point – or if an entirely different robot is used, then an additional connector can simply be 3d – printed. This greatly improves that utility of the core features of the design. This type of engineering is what differentiates plastic toys from Legos – reusability.

3.6 Drive Train Design

While the design and creation of different mechanical elements in order to transfer power through systems is not as important of a facet of mechanical engineering as it once, it is still an interesting area of design. In spite of perhaps common sense, I decided to redesign the entire gear train for the motors. The reason for this choice is to make the whole package fit into a smaller area while also attempting the challenge of building as efficient as possible of a gear train. Since every instance where power is passed through one set of gears, over 10% of the energy in the system is typically lost [8]. Because of this, the most efficient gear trains use spur gear with a very large difference in relative sizes. Several possible types of power transmission were investigated. Initially I thought the design of a friction based drive utilizing the large radius of the central disk combined with the small but fast radius of the motors would be effective, but the friction interaction proved complicated. Belts were also considered as they have an excellent efficiency (Approaching 99% under good conditions) [8] but were not used for due to geometric considerations.

The previous gear system used in the second design iteration involved four sets of spur gears, with three of those inside the VS-11 servo. The total reduction was about 1:1000, for an average of 1:5.6 per stage. The new gear train uses two motors to provide twice the power, with each drive train having only three interacting elements and a total ratio of 1:776, for an average of 1:9.2 gear reduction per stage. This improvement is mostly due to the fine pitch of the large ring gear combined with the small 9 tooth spur driving it. Theoretically this new gear train should be approximately 7% more efficient than the previous one on a ratio basis, due to the more compact nature, but due to inexact manufacturing processes utilized in its construction it is likely not any more efficient than the old design.

3.6.1 Multiple Motors

The second design iteration used only one motor – however I wanted to increase the power while also decreasing the physical bulk of the design. This would be very difficult to accomplish just by using a larger motor without either breaking my principle of symmetry, or the shape and size requirements. I decided to look into different other options. There are definitely benefits to using several small motors as opposed to one motor including redundancy, form factor, ease of power-transmission elements gearing (and the possibility of large reductions due to high ratio of big circle to really small circle), and the possibility of less strain on the gear train due to multiple points of interaction. However they suffer from some significant issues involving efficiency and perhaps complexity. There has been little research (that I can find) on the actual engineering tradeoffs on this approach. The actual benefits of this implementation likely depend on the circumstances. In this case at least it allows for an increase in the power without a concomitant increase in size, which was the design intent.

3.7 YouBot connector and Electronics

In order to connect the claw fixture to the youBot hand, and use the robot controller for its operation, a controller was developed to provide this interface. The motors needed to communicate with the robot system so an arduino –based electrical system was designed in order to run the claw. This system provides for a robust method of accurately positioning the claw, as the details of the encoder control are handled by the arduino microprocessor, and the YouBot-arduino interface only involves low bandwidth general instructions.

A significant problem involved the need to provide connection for up to 6 wires to connect the claw to the robot on the arm. There is one effective way to this which is to use some kind of self-grabbing self-attaching connector. One particularly elegant way to do this is through magnetic connectors like the Apple Mag-safe power adaptor.[11] While this has not actually be designed or built, its construction would aid in the ease of attachment and detachment from the claw, and allow the robot to do this without human intervention.

This is accomplished using an off the shelf Arduino nano microprocessor. The Arduino is programmed in Arduino language which is based on C++ and the interface with the ROS running the youbot is provided through an USB cable and using several existing arduino-ROS programming modules [13].

4. Results and Experimentation

4.1 General Results

The claw fulfilled the primary goals of improved weight, performance and size. The new claw is adequately able to attach the Table leg to the Lak table as shown in figure 4-1.

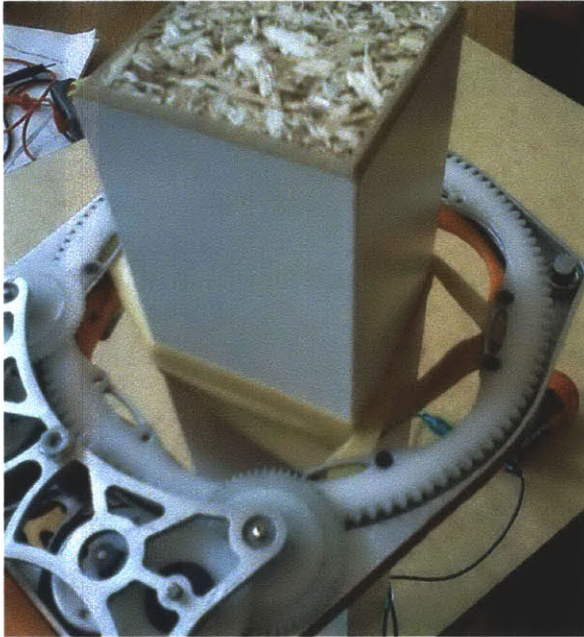


Figure 4-1. Attaching Leg. Figure showing the new claw attaching a Lak table leg to the table.

The claw was also adept at picking up additional objects, including smaller objects such as 9-volt battery due to its smaller bulk. While there are components of the project that are unfinished, the design works and hopefully will be improved in the near future.

4.2 Grasping characterization

While the previous design just happened to work, this is an unacceptable rationale for high-performance machines. The general dynamic situation is can be seen in figure 9.

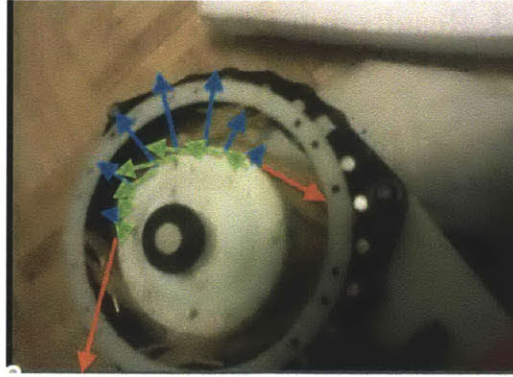


Figure 4-2. Showing the model of the interaction between the elastic encircling elements and the object being gripped. Figure 2. Red arrow shows tension force, Blue shows normal force (On the bottle) and green shows the frictional forces, which combine to create the torque on the object.

The way to analysis this is to use equation 1: the Capstan equation [8] This equation makes a connection between the coefficient of friction, the contact arc, and the effective tension

$$\text{Equation 1} \quad T_{\text{load}} = T_{\text{hold}} e^{\mu\phi}$$

(or torque) that the element provides. As the angle of contact increases, the maximum torque increases exponentially. This means that roughly once the bands are wrapped around sufficiently around the object, the system in fact becomes self-tightening, and will work until either the motor torque is over come, or the encircling bands break. The required angle for self-tightening can be estimated to be when T_{hold} is \gg than T_{load} . In terms of rubber bands (μ for rubber is around 1), this condition is met around an angle of $\pi/2$ degrees. This fact that it “just worked” in previous designs is due to the very high degree of forgiveness that the system provides due to the self-tightening behavior exhibited in the capstan equation.

However a more detailed analysis of the performance of different elastic elements and the coefficient of friction between the elements can be inferred from figure 4-2. This graph shows the combined torque factor (Tension inputted divided by tension Output) that increases exponentially for a range of different coefficients of friction.

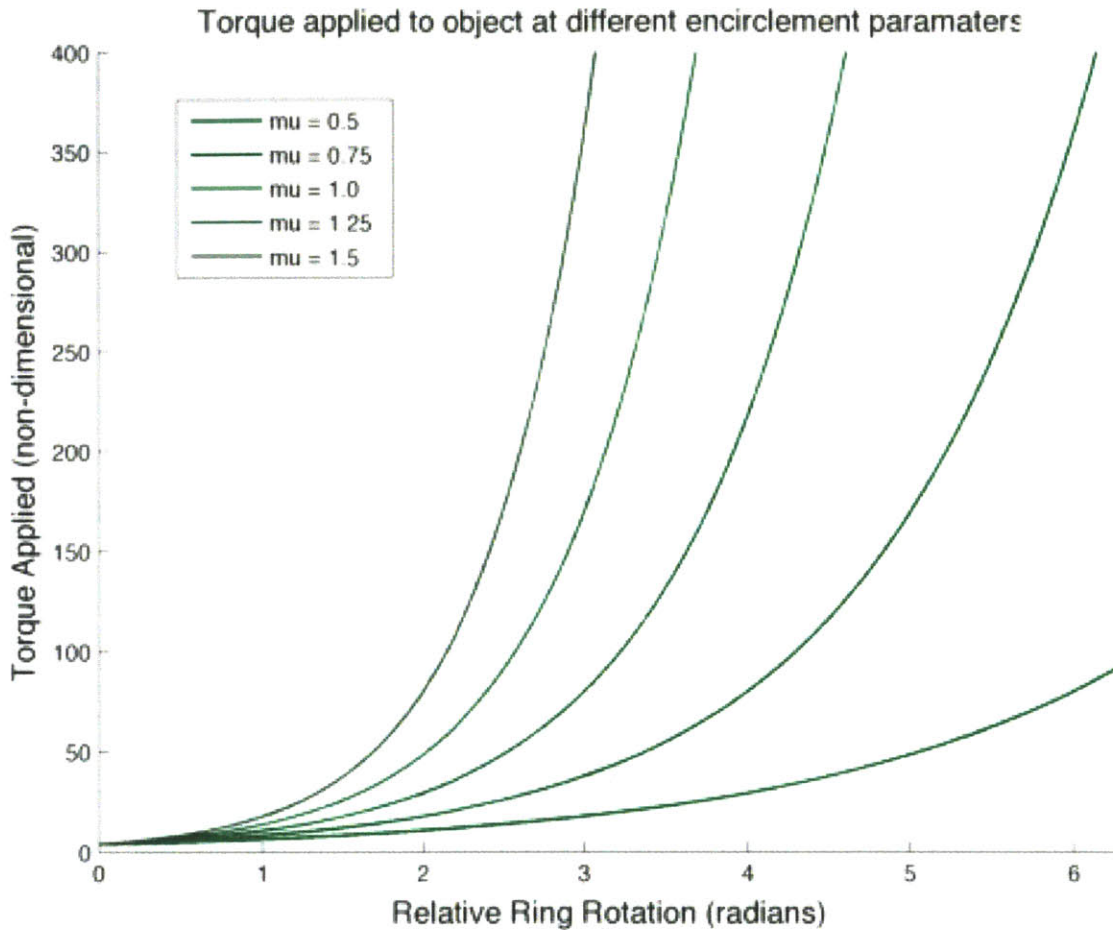


Figure 4-3. Tension characterization graph – showing the amount of torque provided under different interactions between the elastic members and the object being grasped

This model provides an incredibly wide range of diameters, surface roughness's, number of rubber bands and due to the self-tightening capstan effect of the rubber pulleys. Since the coefficient of friction between the objects depends on a diverse array of factors, including the objects shape and surface properties, figure 4-3 shows us that for almost any combination of these factors, a high degree of grasping torque can be provided due to the capstan effect

4.3 Comparison to Original Version

The final prototype looks and behaves more robustly than the initial prototype, and it has twice the power, while being lighter and better looking. The use of high quality engineering materials, including Aluminum allows 7075 and Acetyl Copolymer plastic gives the device improved performance characteristics than the previous design. The prototype claw was tested to grasp and screw in the Lak table leg in four experiments. Each full grasping and operation took an average of around 30 seconds.

Table 4-1 Showing a comparison of the different prototypes

Parameter	Protoype 1	Prototype 2	Final Prototype
Weight	Unknown	360 grams	226 grams
Bounding Box	12x24x13	10x25x13	4x18x13 cm
Cost	\$100 (est)	\$300 (est)	\$460 (est)
Gear ratio	unknown	1:800	1:439

4.4 Discussion

Through designing this product, I learned many things not only about analysis of mechanical design, but also about different machining techniques. I also learned many things about design, FEA software and machining by the work done in this project.

4.4.1 Lessons Learned

- The claw concept can deliver on the desired function to screw in objects of different sizes.
- The claw can deliver the required force and torque for grasping, ungrasping, and rotation of objects.
- Use proper fixtures while machining! I once was turning a complex piece, and it wasn't fixtured correctly, and then it caught on the tool and destroyed itself.
- Think out Process plans for complex machining processes before beginning work on them.
- Servo gear-trains are amazingly designed and efficient for machines that cost under ten dollars.
- Complicated projects can cause all different kinds of problems that cascade into one another in order to cause delay in the project. Organization is key in order to mitigate these problems.

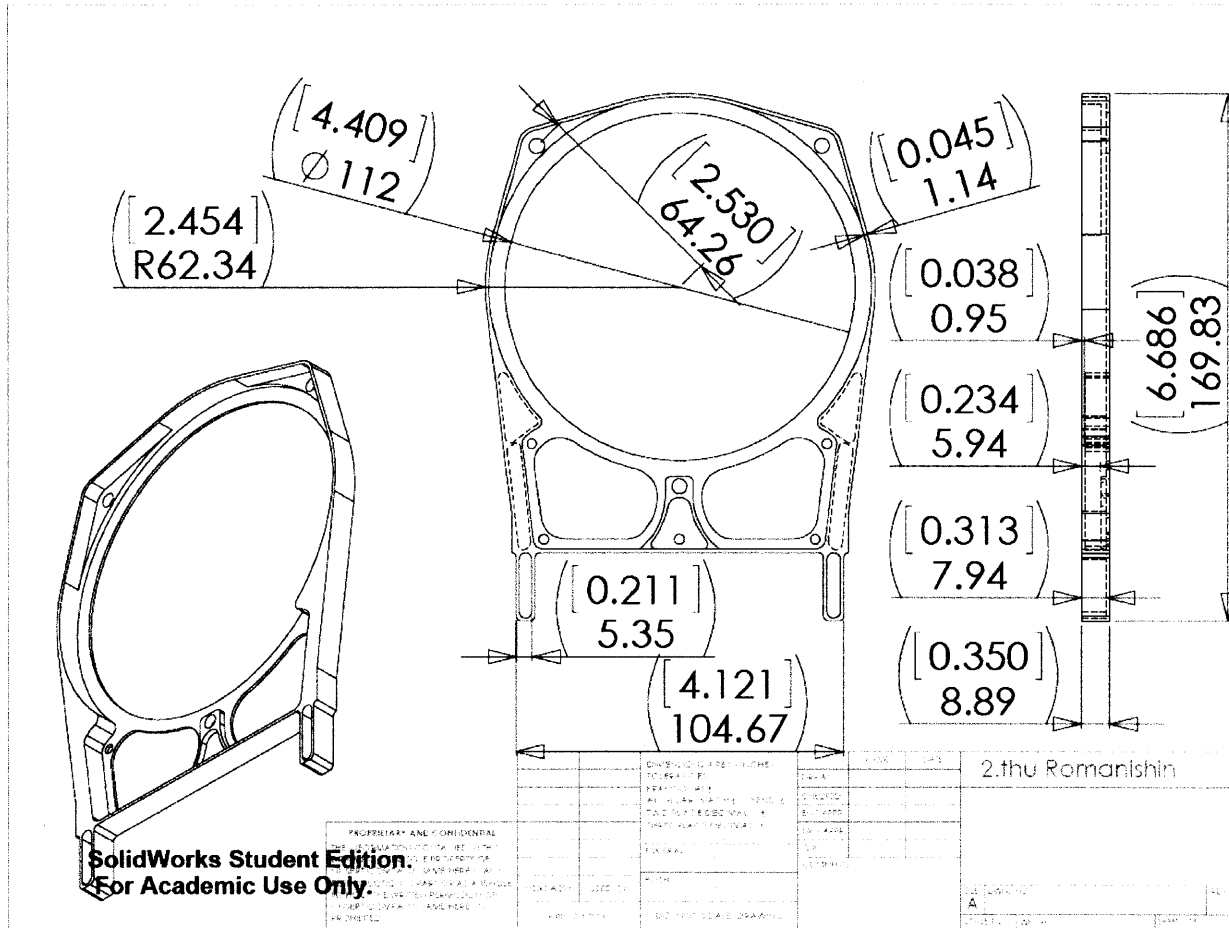
4.4.2 Future Work

In the short term, the integration of the claw with the YouBot and extensive autonomous manipulation experiments are required so that a technical paper can be written to discuss the concept, problems, algorithms and challenges involving assembling furniture with Youbots.

One fascinating thing I would like to work on is using this type of claw in order to help robots use human tools. Future robots, in order to make them the most versatile while assembling things, will want to have access to human tools such as screw-drivers, wrenches, hex drivers, hand-drills, while ideally robots would not need to carry around multiple different claws in order to use these tools, some device capable of continuous spinning would be helpful for these tasks. The other key aspect of this claw is its ability to handle very delicate objects, the same type of design that uses the encirclement of objects by elastic elements could be used for all kinds of purposes, not only to spin objects.

Appendices

Appendix A. Technical drawing of aluminum frame



Appendix B. Matlab Code

```

1   % plotaccelerationclip
2 - hold off
3   %scrsz = get(0,'ScreenSize');
4   %figure('Position',[1 scrsz(4)/2 scrsz(3)/2 scrsz(4)/2])
5 - set(figure, 'color', 'white'); % sets the color to white
6 - hold on
7   %#####
8 - xlabel('Relative Ring Rotation (radians)')
9 - ylabel('Torque Applied (non-dimensional)')
10 - title('Torque applied to object at different encirclement paramaters')
11 - h_xlabel = get(gca,'XLabel');
12 - set(h_xlabel,'FontSize',13);
13 - b_xlabel = get(gca,'YLabel');
14 - set(b_xlabel,'FontSize',13);
15 - c_xlabel = get(gca,'Title');
16 - set(c_xlabel,'FontSize',13);
17 - axis([0 2*pi 0 400])
18 %#####
19 - mu = 0.5
20 - mu1 = 0.75
21 - mu2 = 1.0
22 - mu3 = 1.25
23 - mu4 = 1.5
24
25 - range = [0:0.01:2*pi]
26 - c = 4.*exp(mu*range)
27 - c1 = 4.*exp(mu1*range)
28 - c2 = 4.*exp(mu2*range)
29 - c3 = 4.*exp(mu3*range)
30 - c4 = 4.*exp(mu4*range)
31 - legend('mu = 0.5','mu = 0.75','mu = 1.0','mu = 1.25','mu = 1.5')
32
33
34 - run1 = plot(range,c,'color',[0 1 0],'LineWidth',1.0)
35 - run2 = plot(range,c1,'color',[0 0.8 0],'LineWidth',1.0)
36 - run3 = plot(range,c2,'color',[0 0.6 0],'LineWidth',1.0)
37 - run4 = plot(range,c3,'color',[0 0.4 0],'LineWidth',1.0)
38 - run5 = plot(range,c4,'color',[0 0.2 0],'LineWidth',1.0)
39 %run6 = plot(datax,datay,'color',[0 0.2 0],'LineWidth',1.0)
40
41 - legend('mu = 0.5','mu = 0.75','mu = 1.0','mu = 1.25','mu = 1.5')
42
43 %set(hlegend,'FontSize',13);
44 %actualdata = degrees [0 80 grams 300 700 1000+]
45 %actualdata = torque exerted [0 15 30 45]

```

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